

TEM, LEAP, and Interfacial Defects of AlGaIn/GaN HEMTs

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G A T O R
Engineering



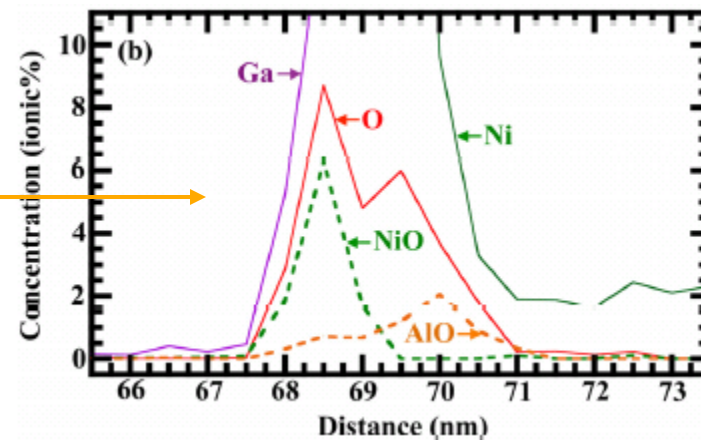
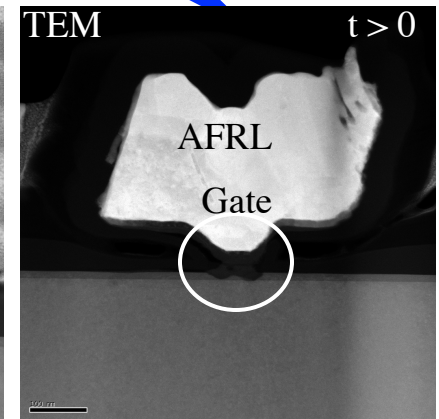
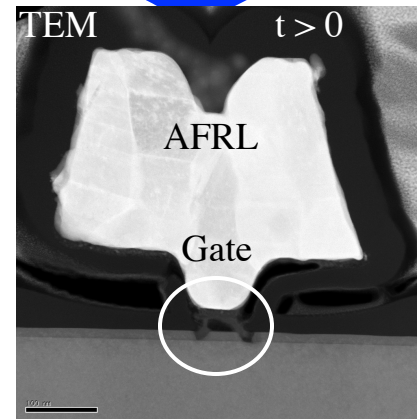
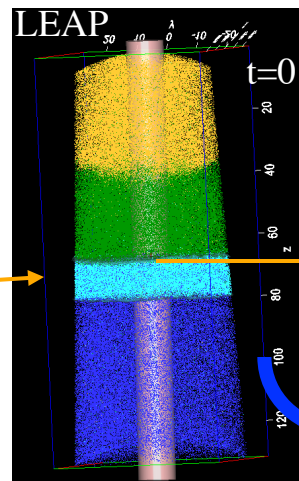
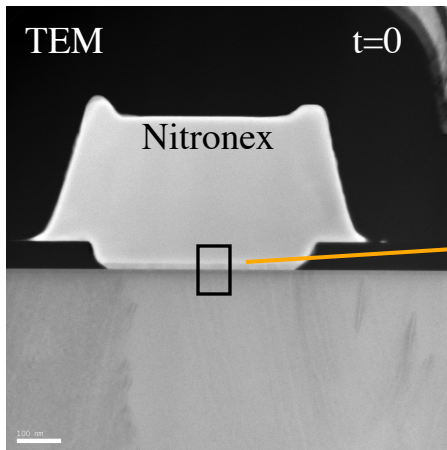
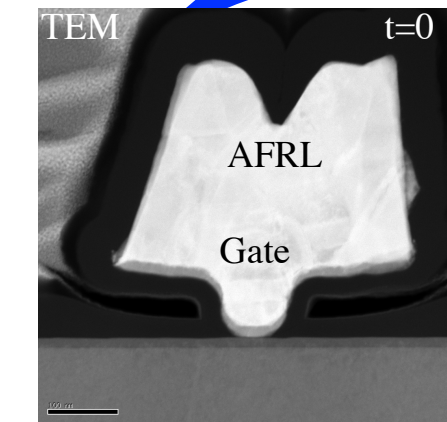
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FLORIDA

TEM, LEAP, and Interfacial Defects of AlGaN/GaN HEMTs

$t=0$, As Built

FLOORS

$t>0$, Degradation

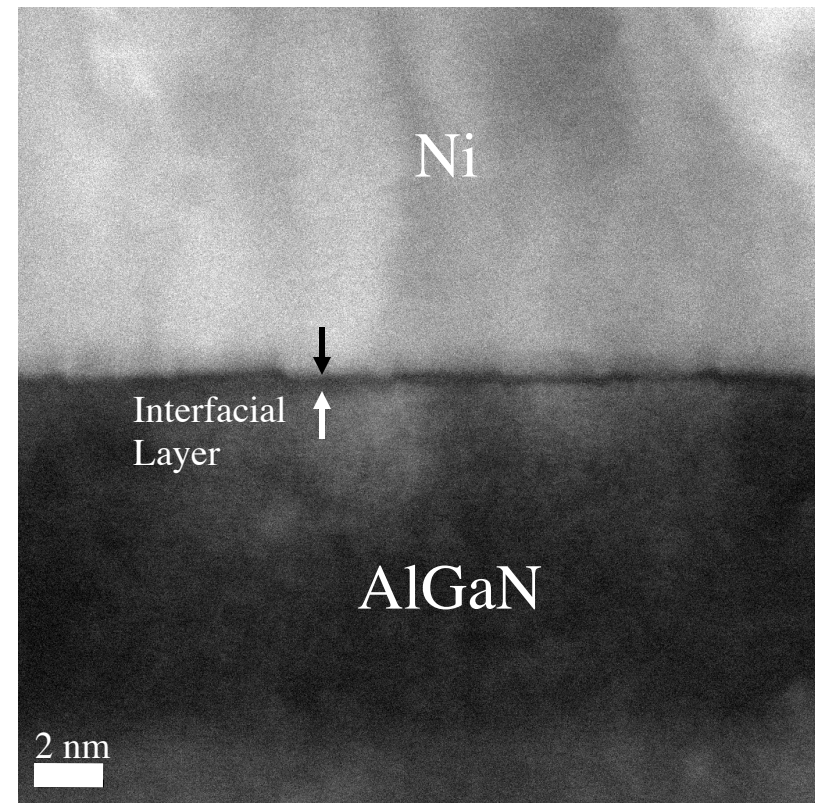
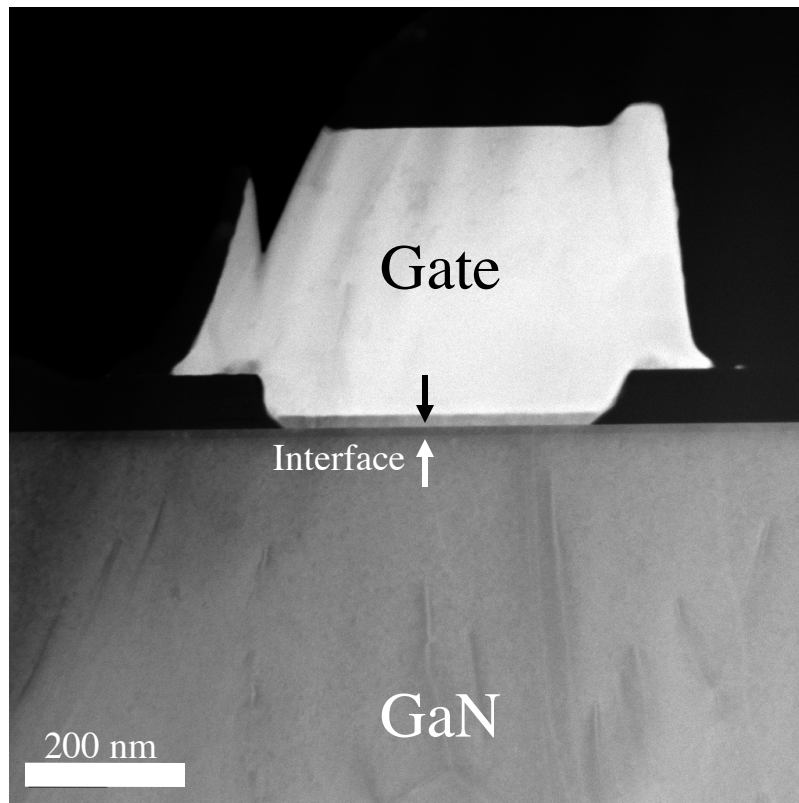


Outline

- Devices Analyzed
 - Nitronex (Ni-gate) ($t = 0$)
 - TEM
 - Interfaces
 - LEAP
 - Review
 - Data Reanalysis \rightarrow Improved Results
 - MIT (TriQuint) (Pt-gate) ($t > 0$)
 - Update on Collaboration
 - TEM
 - Interfaces and Defects
 - LEAP
 - Angled tip and results
 - AFRL (Ni-gate) ($t = 0$ and $t > 0$)
 - TEM
 - Interfacial defects
 - LEAP
- Limitations of LEAP
- Current Collaborations
- Conclusions
- Future Work

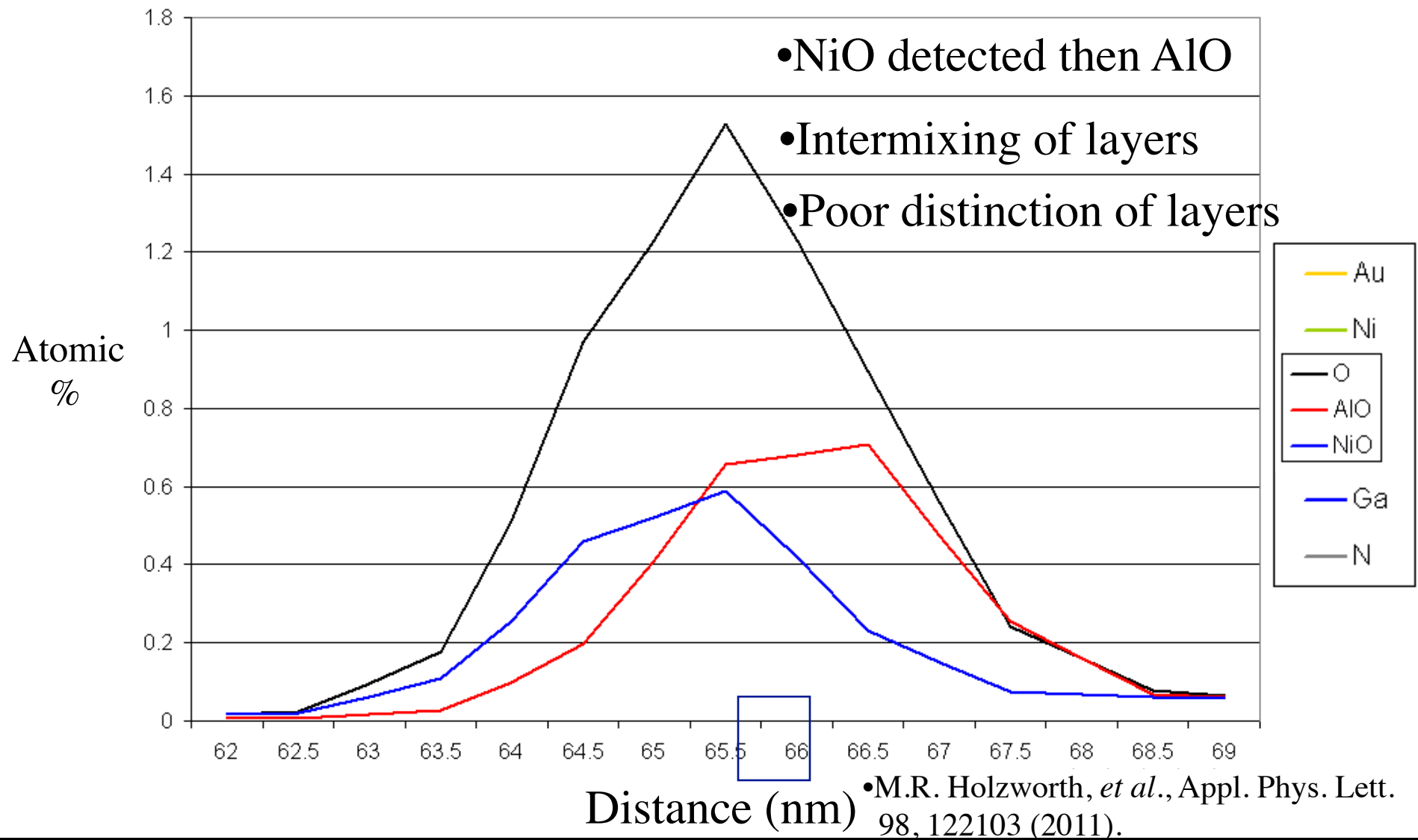
TEM of Nitronex Gate/Epi Interface

- TEM (STEM-HAADF)
 - $t = 0$



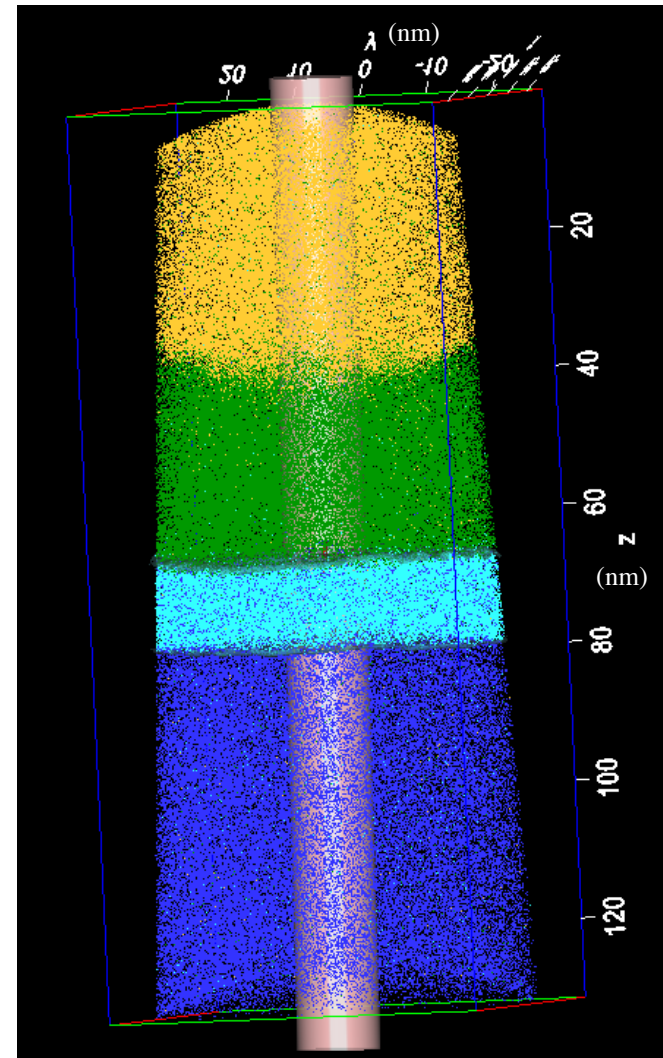
- Interfacial layer is $\sim 5\text{\AA}$
- Composed of NiO_x and AlO_x (LEAP)

Last Review: 1-D Concentration Profile (Nitronex)

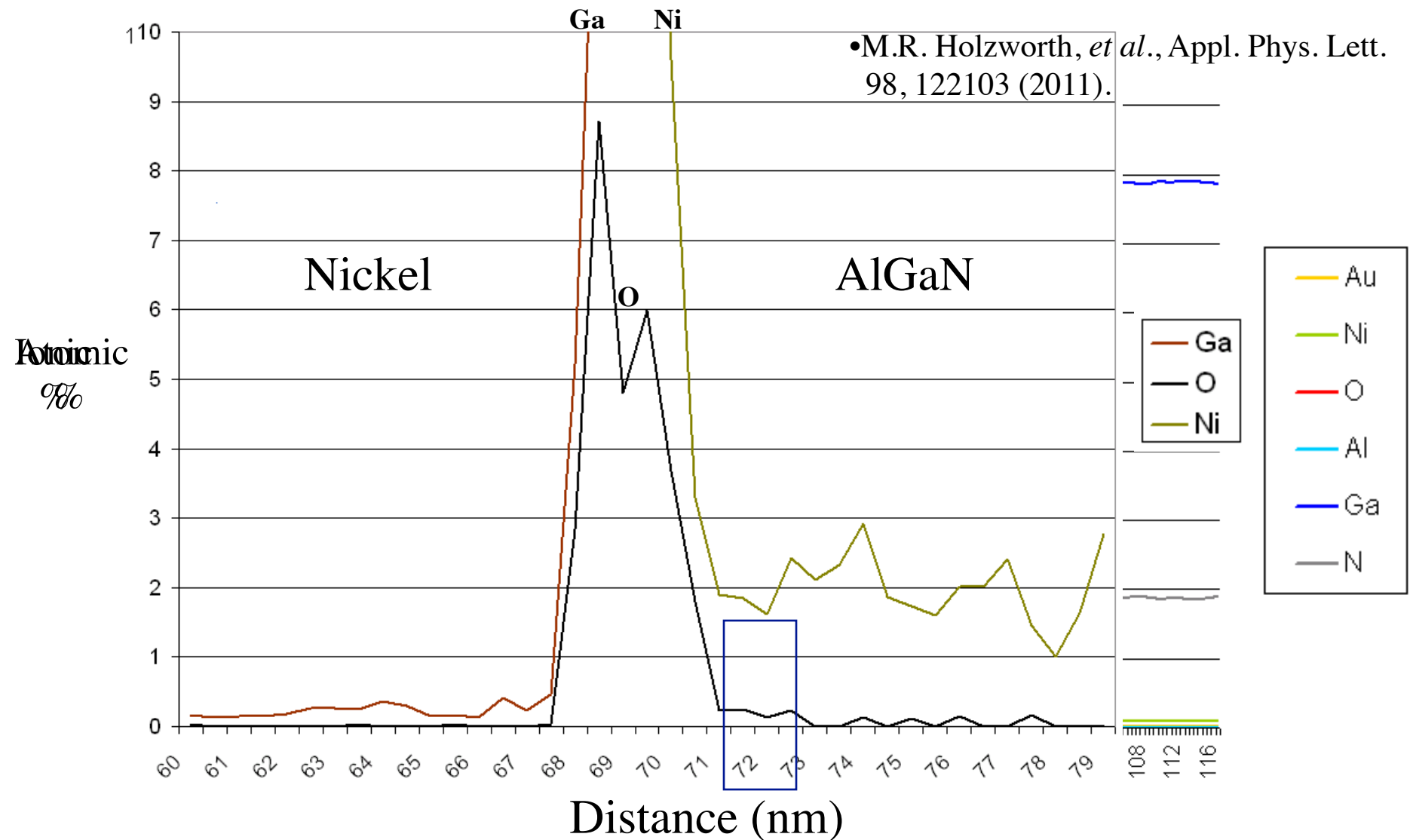


How is Data Reanalyzed for Greater Accuracy?

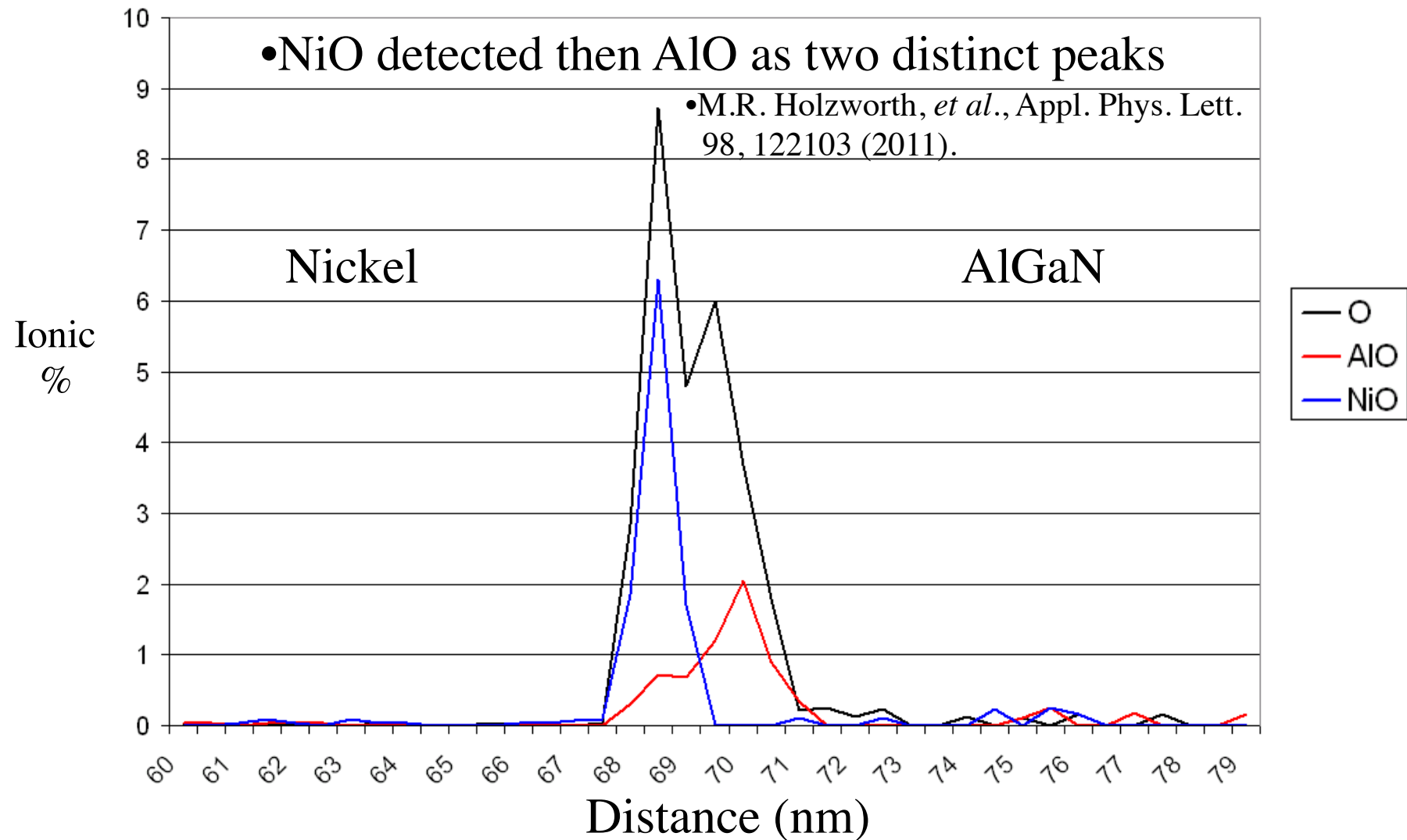
- Find the iso-surface
- Position data pipe relative to iso-surface of interest
- Use data pipe to collect information
 - Analysis occurs along the length of the pipe and across the cross sectional area



Closer Inspection of the 1-D Concentration Profile (Nitronex)

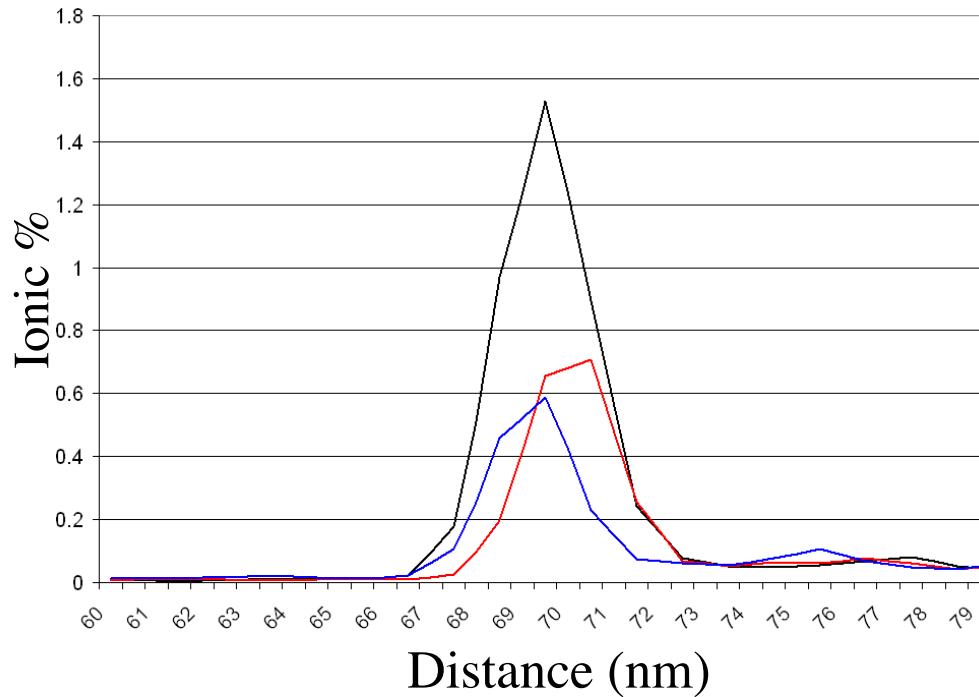


Closer Inspection of the 1-D Concentration Profile (Nitronex)

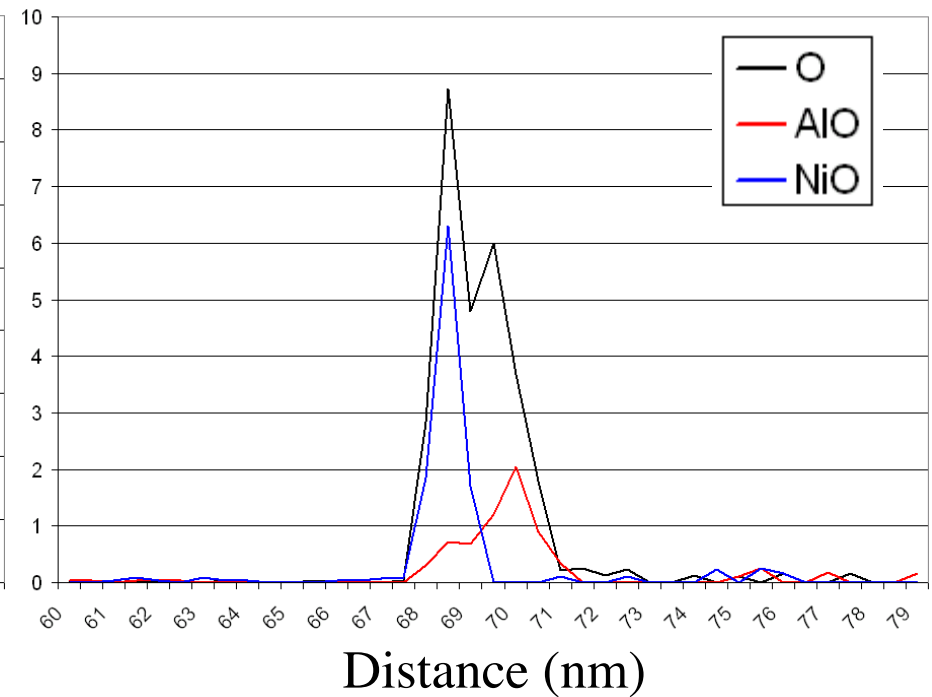


Comparison between 1-D Profiles (Nitronex)

- Before



- After



- Improved interface resolution
 - Layer abruptness increased (6 nm vs 3.5 nm)
 - Layer mixing is decreased (distinct oxide layers)

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Update on MIT Collaboration

- Collaboration
 - Prof. Jesus del Alamo at MIT
 - Group suggested the inverse piezoelectric effect for failure and have done the initial work in the area
 - TriQuint Devices
- They provide us with unstressed and stressed fingers on a device
- We provide:
 - TEM
 - Image defects (non-uniform along gate width)
 - LEAP
 - Determine the composition of the pit and crack defects
 - Knowing composition would help formulate formation mechanisms for defects

Update on MIT Collaboration

- 6 Slides redacted

Update on MIT Collaboration

- MIT (TriQuint) devices fracture at interfaces using LEAP
 - Thick interfacial layer between the gate and epi-layers attributes to LEAP tip fracture and delamination
 - Inhibits acquisition of composition of pit defect near interface
 - Using a different LEAP or atom probe system with a smaller laser wavelength may correct this issue
- TriQuint has no further interest in this collaboration

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 - LEAP
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Defects Overview

- Observe defects from different stress conditions
- Characterize defects:
 - Chemical
 - Structural

Using:

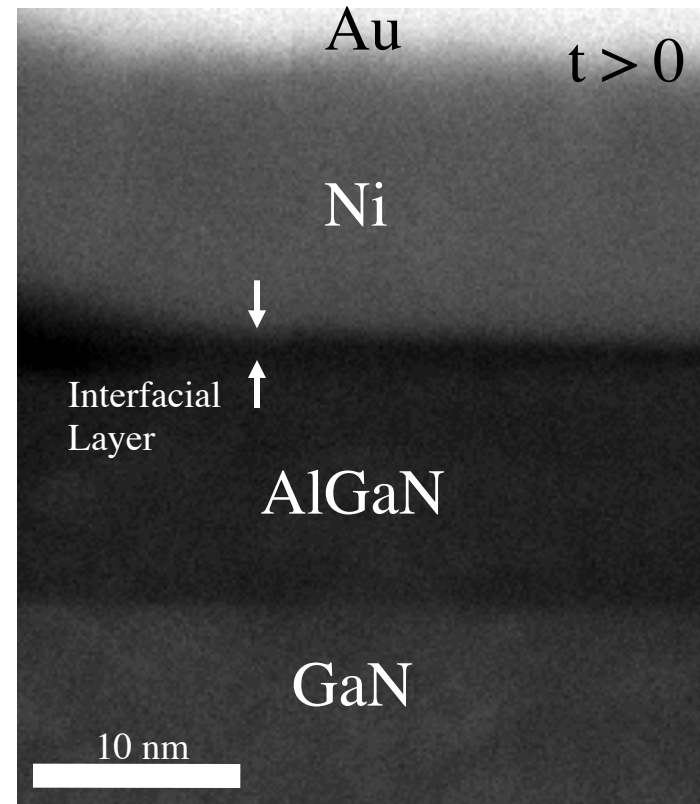
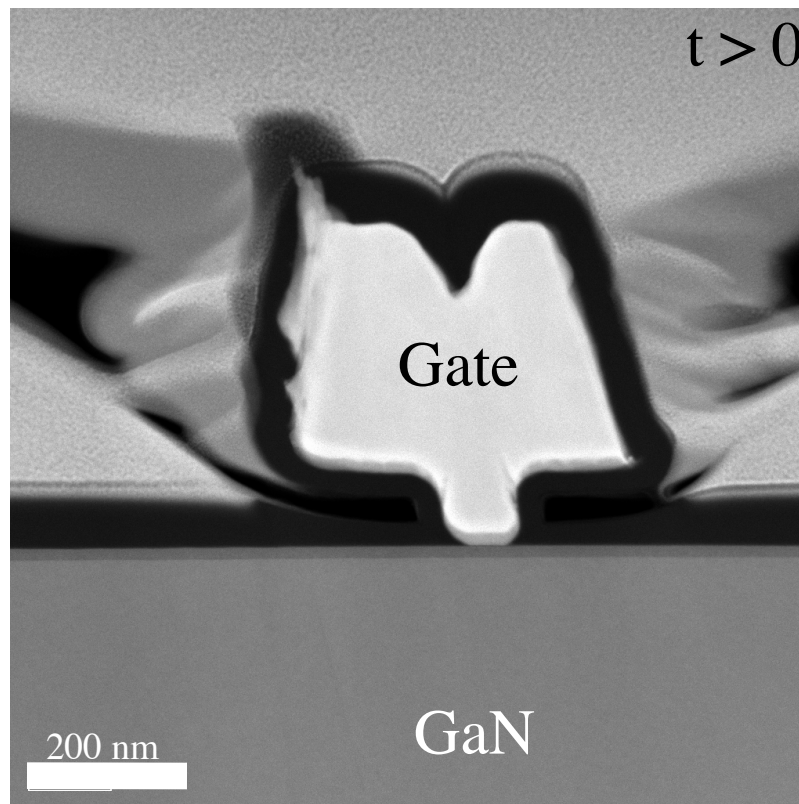
- TEM
 - EDS
- Atom Probe

To determine possible failure mechanisms:

- Improve reliability
- Improve modeling

TEM of AFRL Gate/Epi Interface

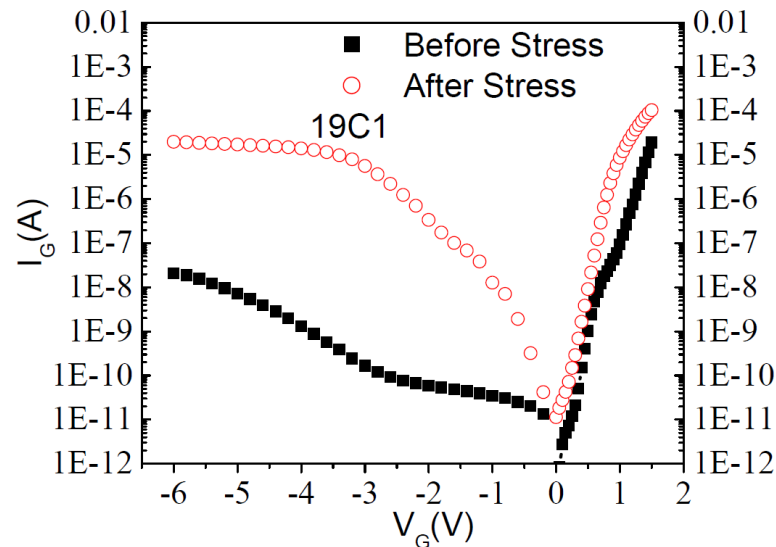
- TEM (STEM-HAADF)
 - Ni-gate



- Interfacial layer is $\sim 15\text{\AA}$
- Unknown composition

AFRL Device 1514

- Device History
 - Made by: AFRL
 - Electrically stressed by: Dr. Ren's Group



- TEM analysis by: Dr. Jones's Group

AFRL Device 1514

- TEM (STEM-HAADF)

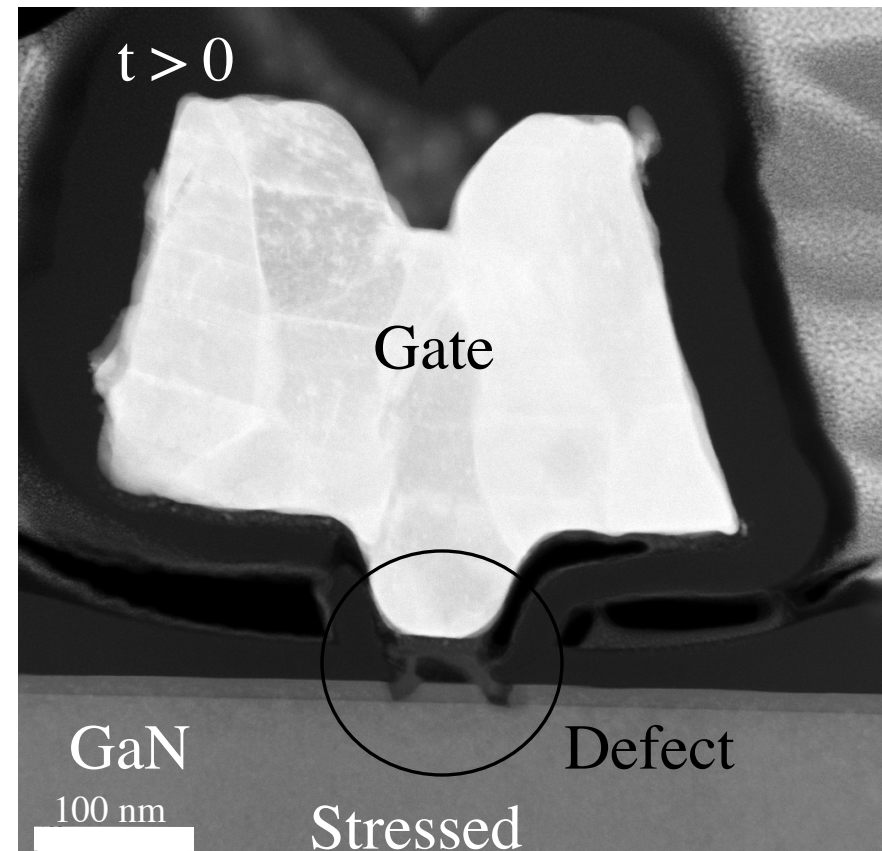
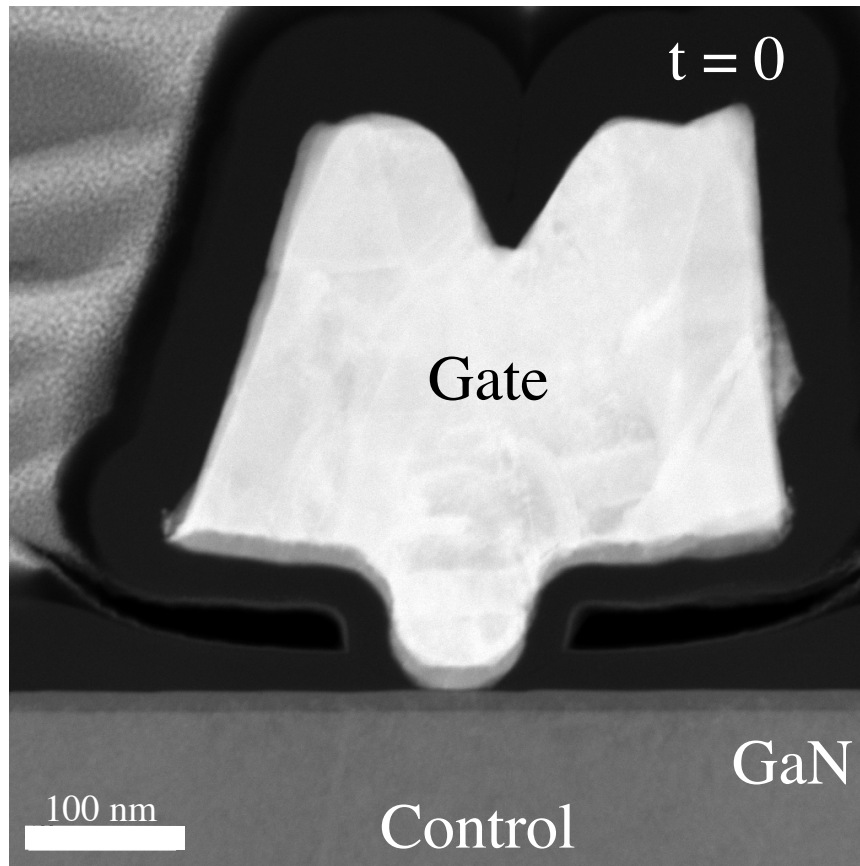
- 100nm L_G
- Ni-gate

Stress Conditions

$$V_{DS} = 5V$$

$$V_G = -5V \text{ to } -42V$$

- 1 min steps



AFRL Device 1514

- TEM (STEM-HAADF)

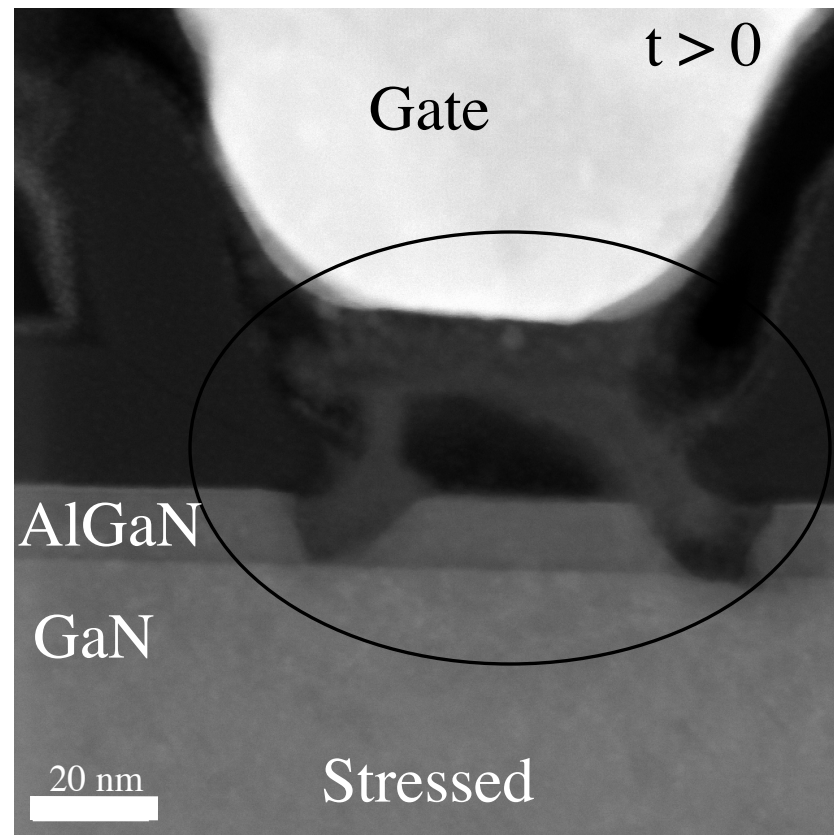
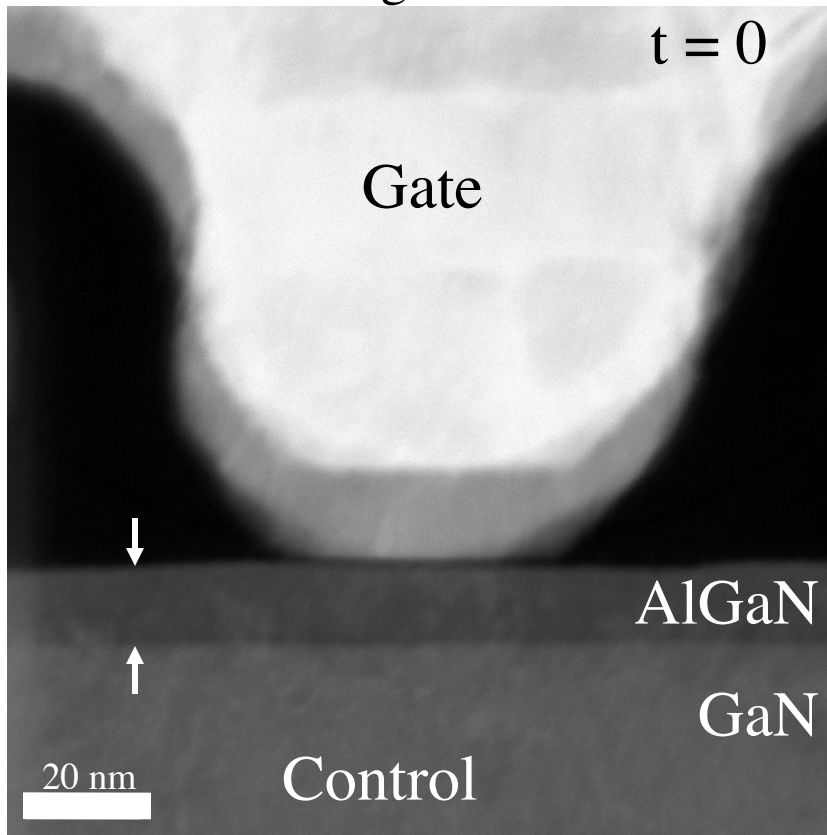
- 100nm L_G
- Ni-gate

Stress Conditions

$$V_{DS} = 5V$$

$$V_G = -5V \text{ to } -42V$$

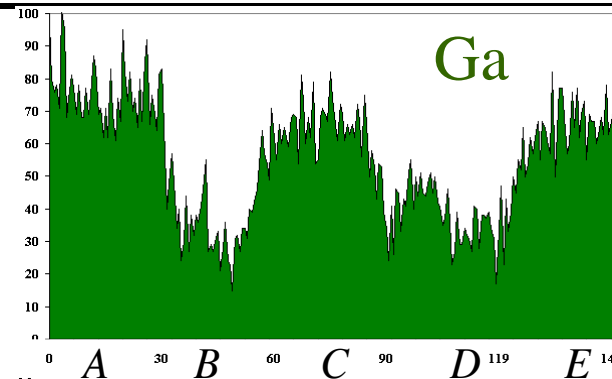
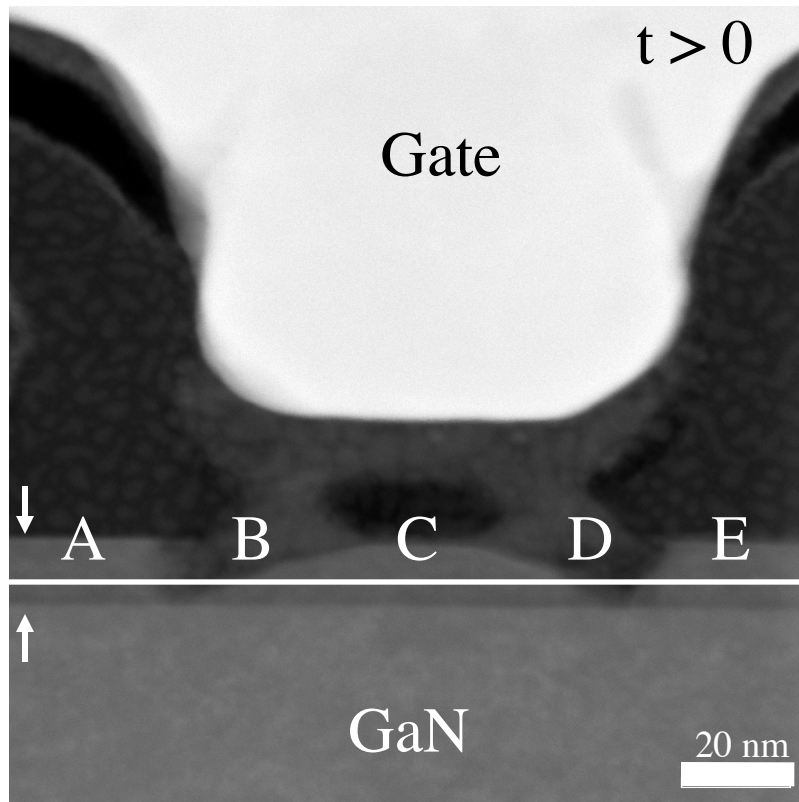
- 1 min steps



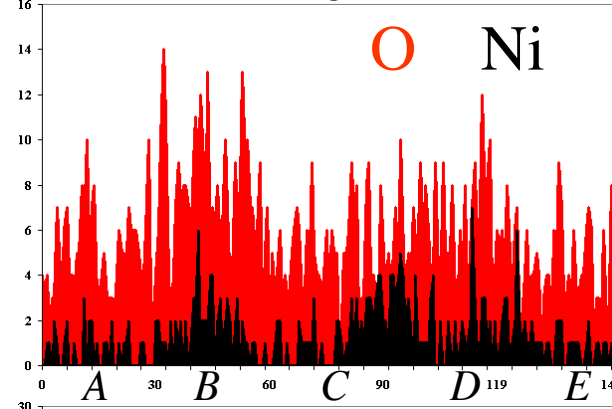
• Defect present

EDS Line Scan across AlGa_N Layer of 1514

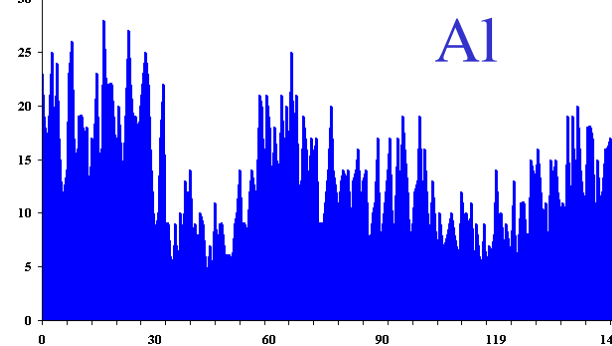
- TEM (STEM-HAADF)
 - 100nm L_G
 - Ni-gate



•Ga decreases in the arch feet



•Ni and O increase in the arch feet

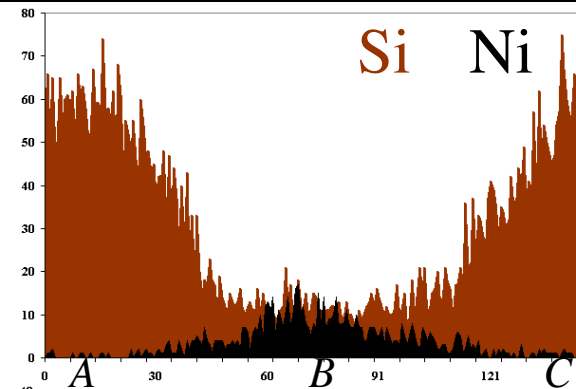
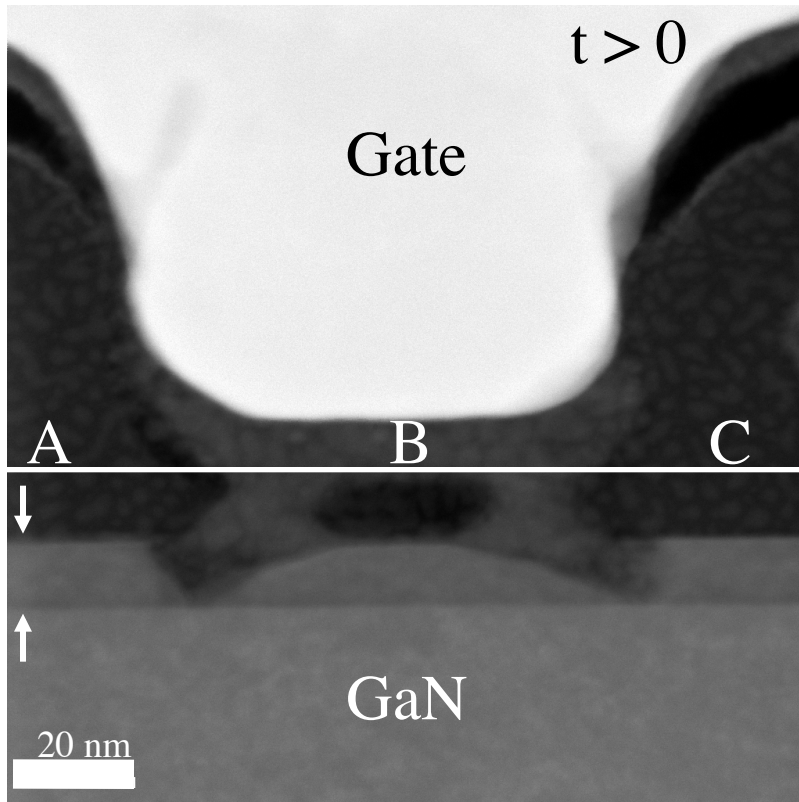


•Al decreases in the arch feet

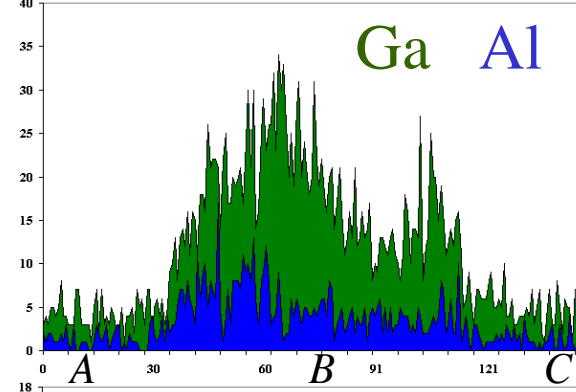
Distance (nm)

EDS Line Scan across Defect of 1514

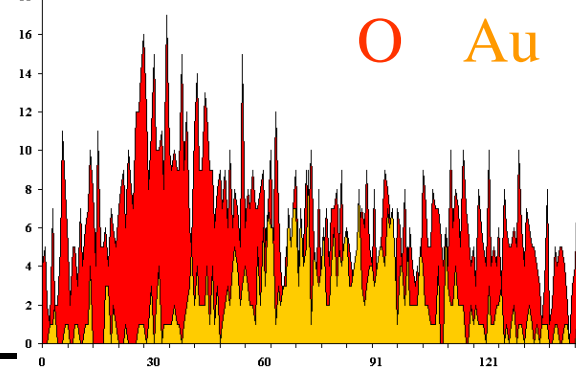
- TEM (STEM-HAADF)
 - 100nm L_G
 - Ni-gate



• Ni detected in the defect



• Ga and Al increase in the defect



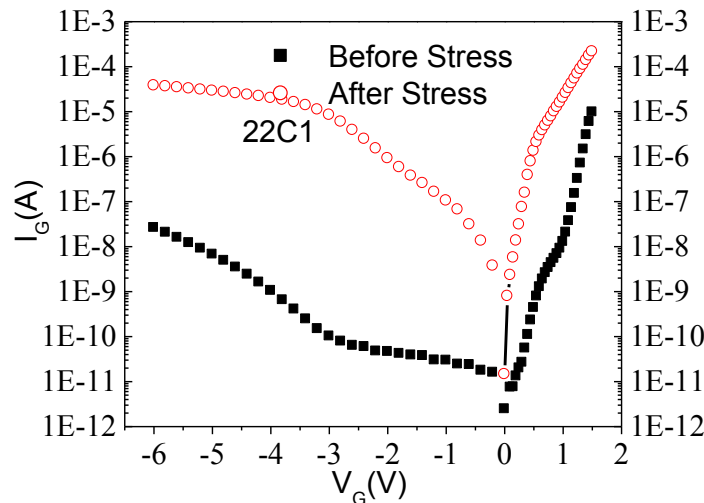
• O and Au increase in the defect

AFRL Device 1514 Conclusions

- Small defect present under 100nm gate
- Found completely throughout the gate width
 - Defect in every TEM and SEM slice
 - Approximately 15 slices
- Defect appears to have different compositions in the Nickel gate region and the AlGaN region
 - AlGaN: Increase in O and Ni
Decrease in Ga and Al
 - Ni: Increase in Au, Ga, Al, and O
None to little Si

AFRL Device 1813

- Device History
 - Made by: AFRL
 - Electrically stressed by: Dr. Ren's Group



- TEM analysis by: Dr. Jones's Group

AFRL Device 1813

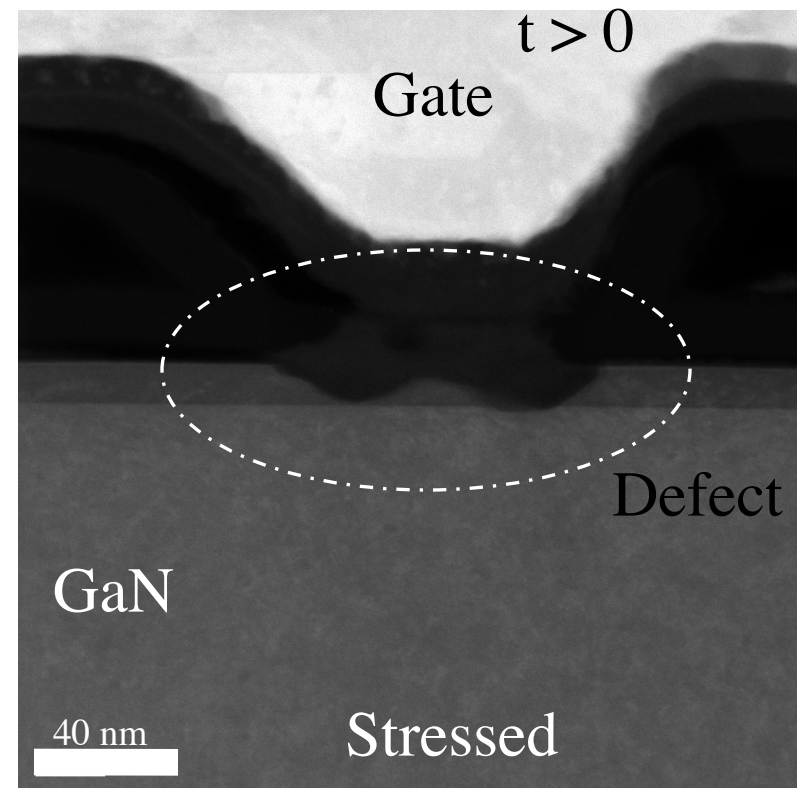
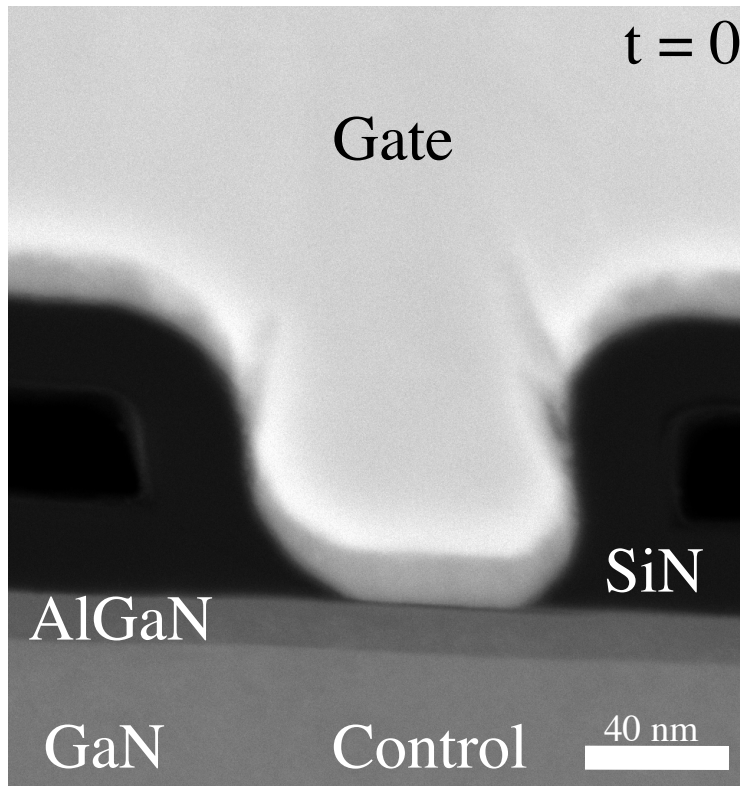
- TEM (STEM-HAADF)
 - 100nm L_G
 - Ni-gate

Stress Conditions

$$V_{DS} = 10V$$

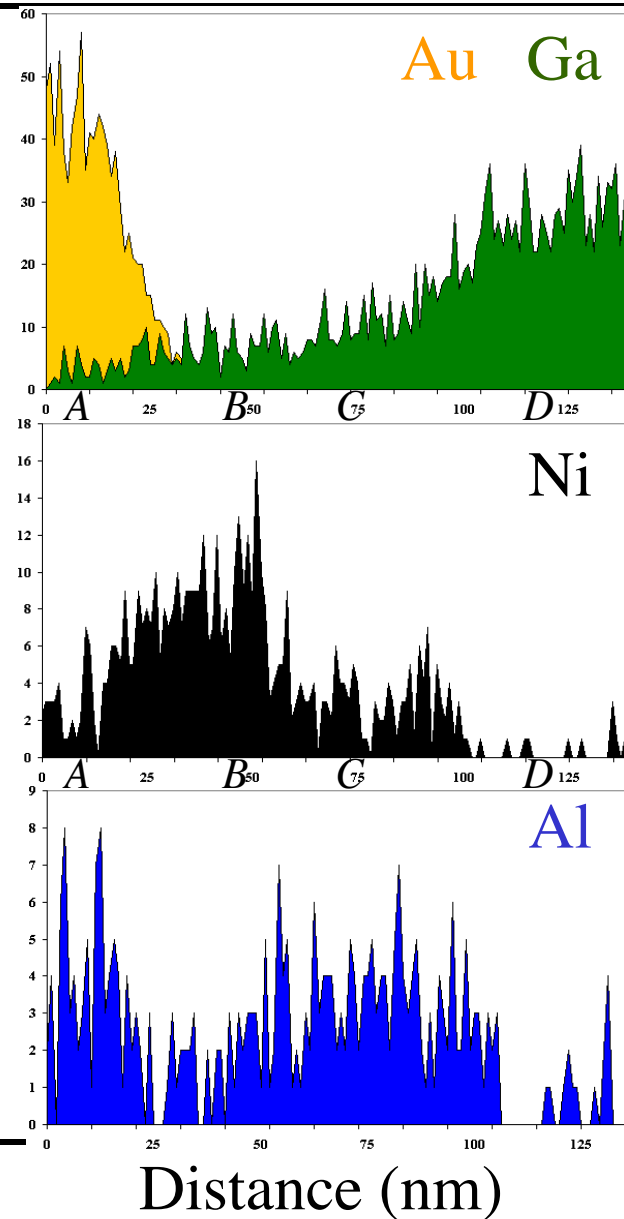
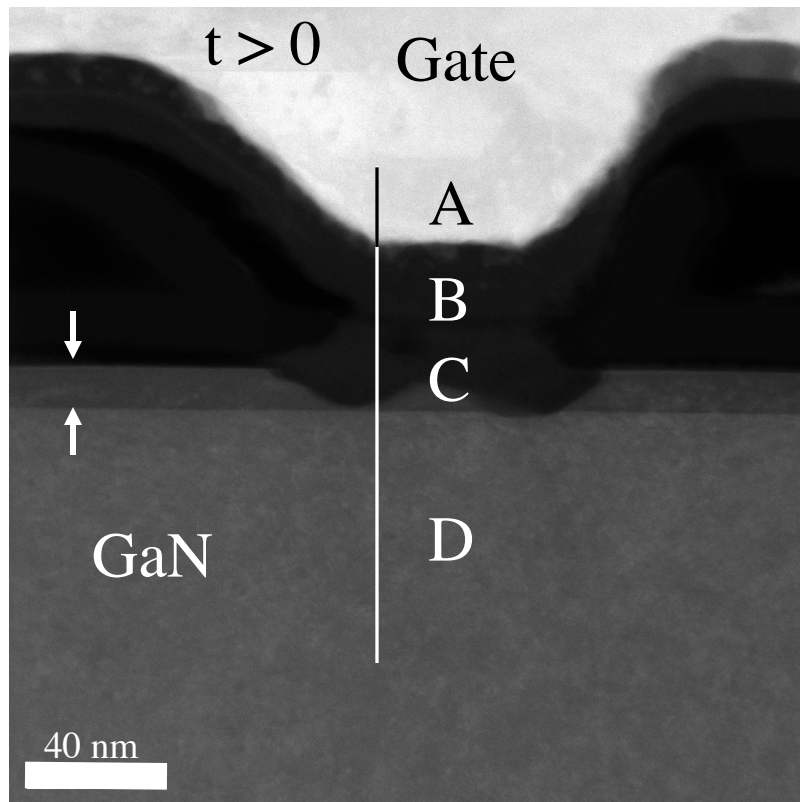
$$V_G = -10V \text{ to } -42V$$

- 1 min steps



EDS Vertical Line Scan through Defect of 1813

- TEM (STEM-HAADF)
 - 100nm L_G
 - Ni-gate



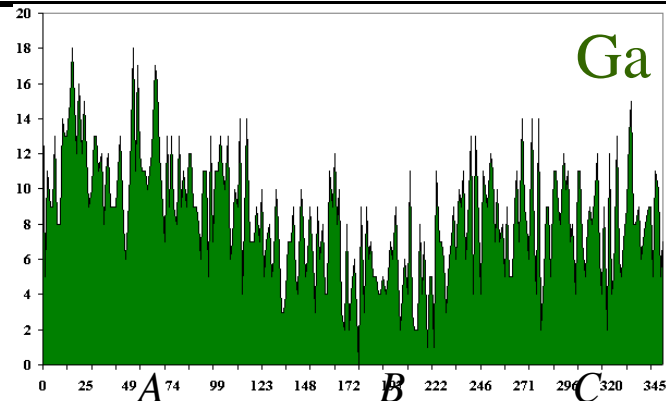
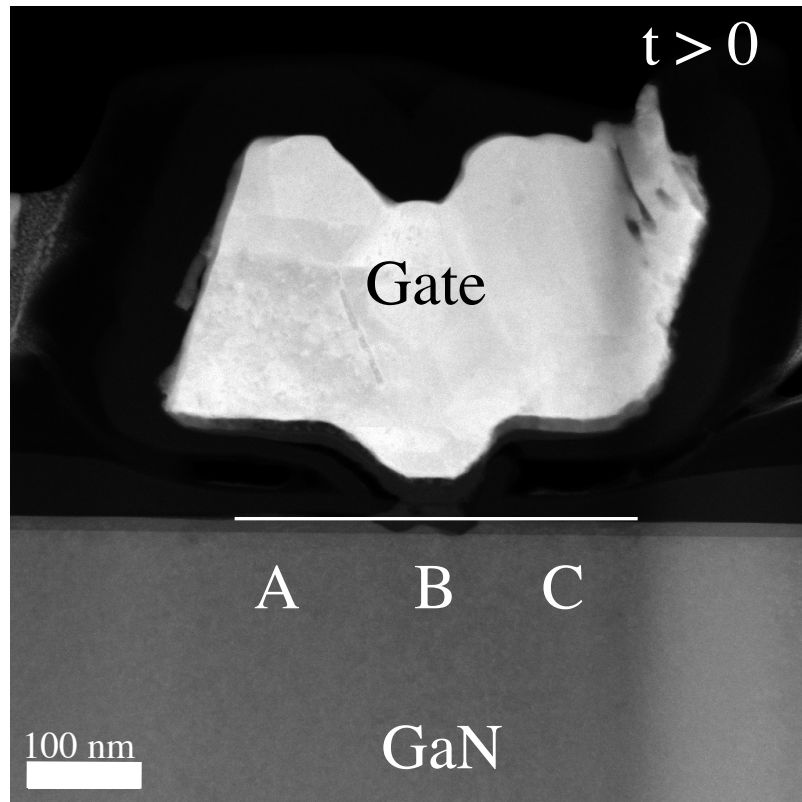
• Increase in Au and Ga in original gate region

• Increase in Ni in AlGaN

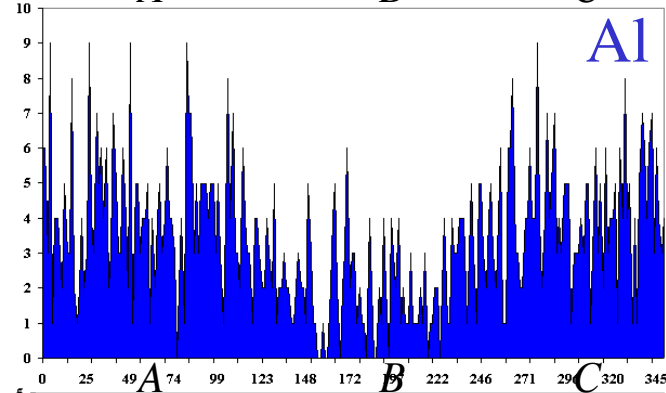
• Increase in Al in original gate region

EDS Line Scan across AlGaN Layer of 1813

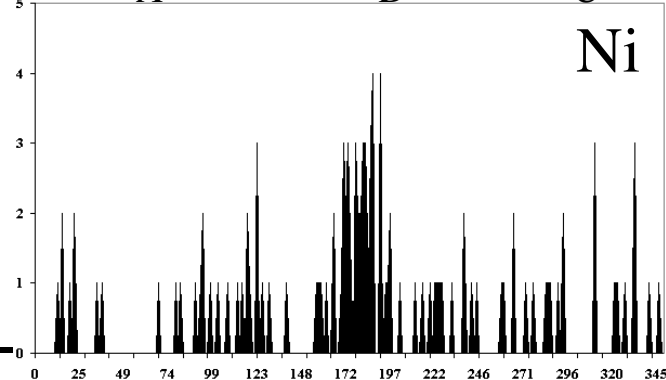
- TEM (STEM-HAADF)
 - 100nm L_G
 - Ni-gate



• Decrease in Ga



• Decrease in Al



• Increase in Ni

Distance (nm)

A 21st Century Approach to Reliability

1813 Conclusions

- Larger defect found completely under 100nm gate
- Not prevalent throughout gate width
 - Found only within 25 microns of an edge
 - Approximately 10 slices
- Defect appears to have different compositions in the Nickel gate region and the AlGaN region
 - AlGaN: Increase in Ni
Decrease in Ga and Al
 - Ni: Increase in Au, Ga, and Al

Defect Comparison

- Two defects observed under high reverse gate bias conditions:

Stress Conditions

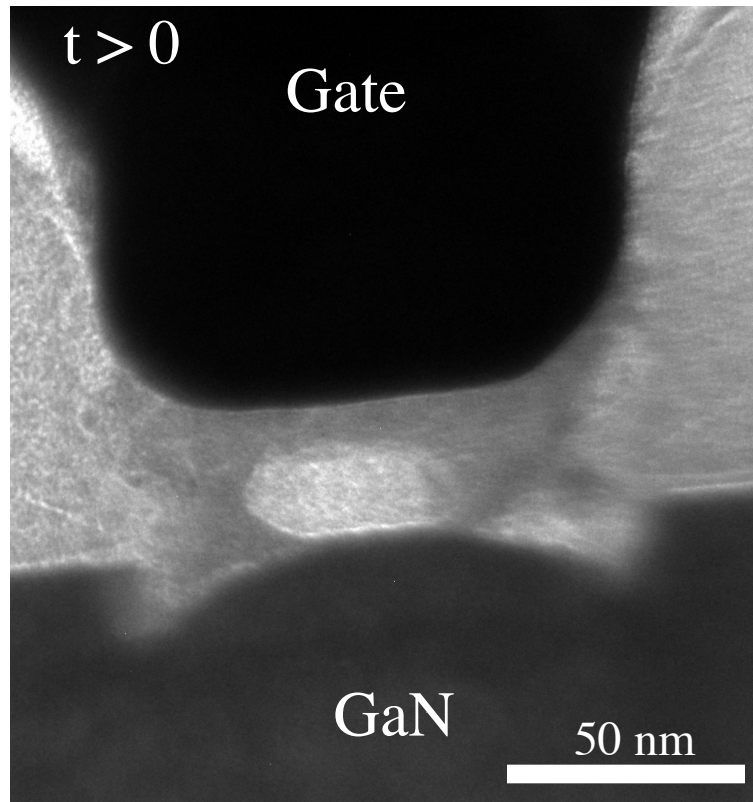
$$V_{DS} = 5V$$

$$V_G = -5V \text{ to } -42V$$

- 1 min steps

- TEM

• 1514



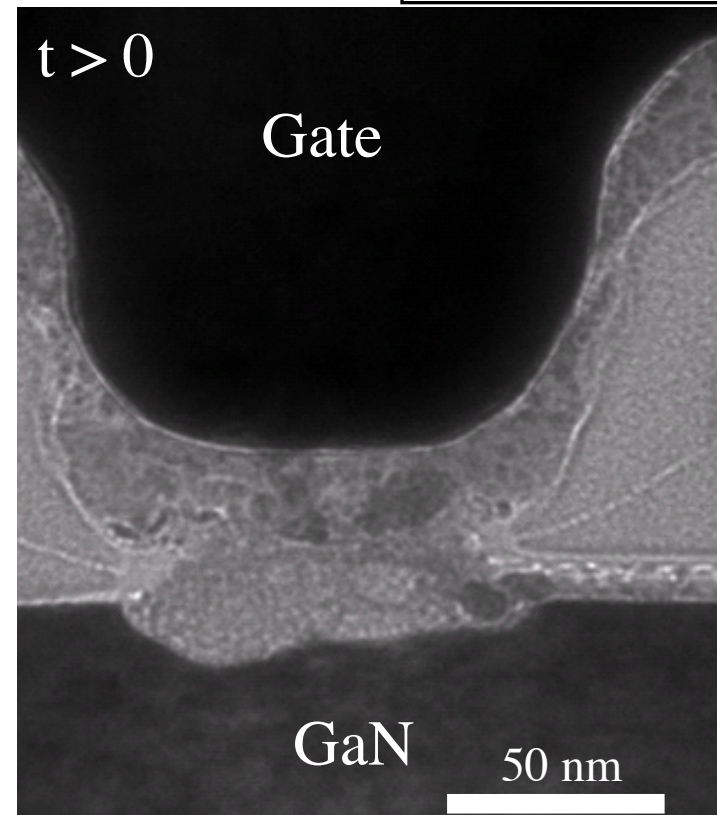
Stress Conditions

$$V_{DS} = 10V$$

$$V_G = -10V \text{ to } -42V$$

- 1 min steps

• 1813



Defect Comparison

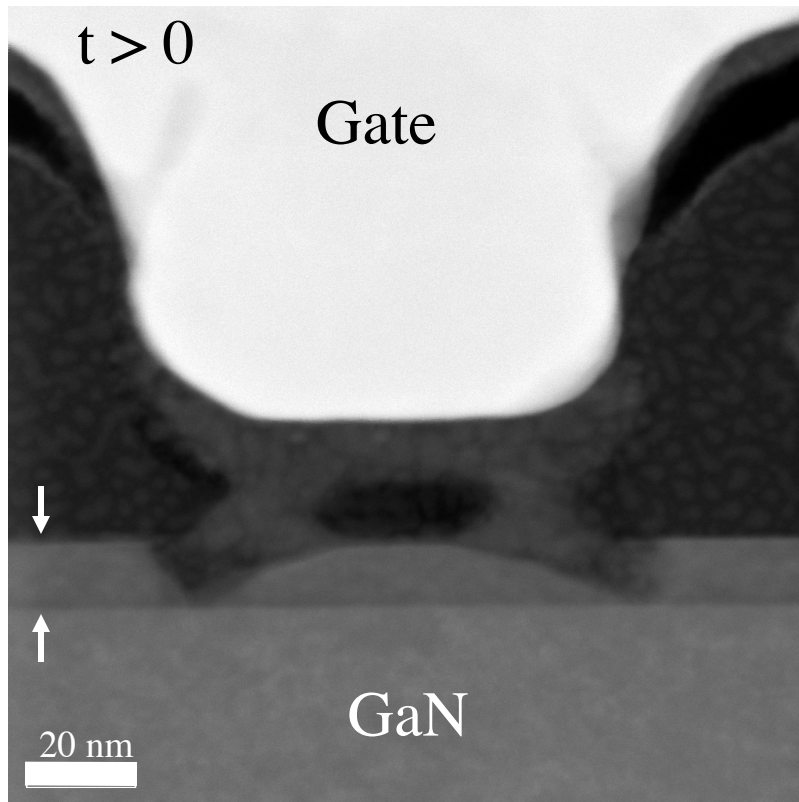
- Two defects observed under high reverse gate bias conditions:

Stress Conditions

$V_{DS} = 5V$
 $V_G = -5V$ to $-42V$
• 1 min steps

- TEM (STEM-HAADF)

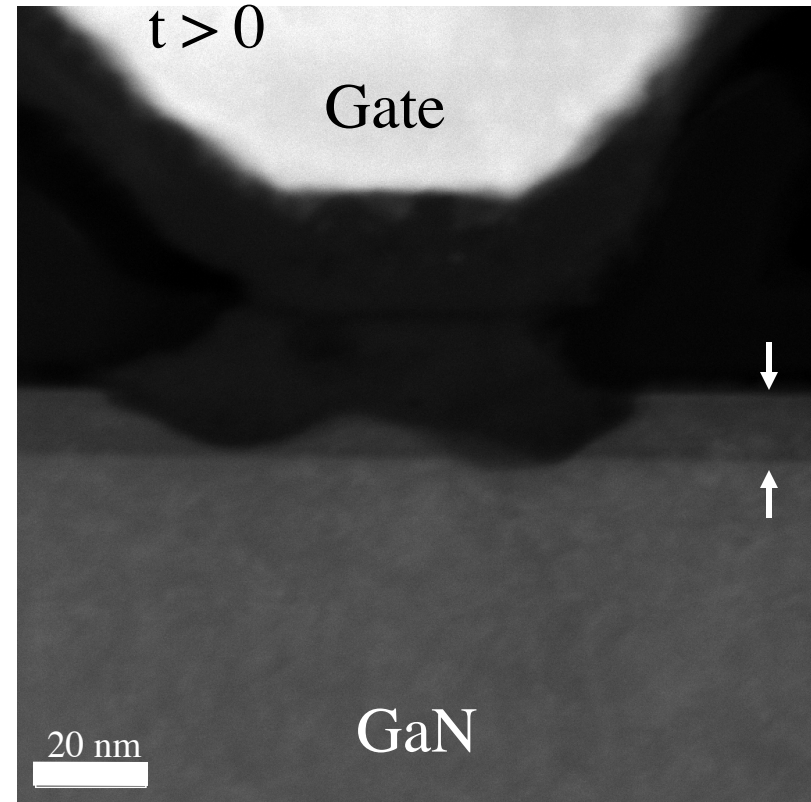
- 1514



Stress Conditions

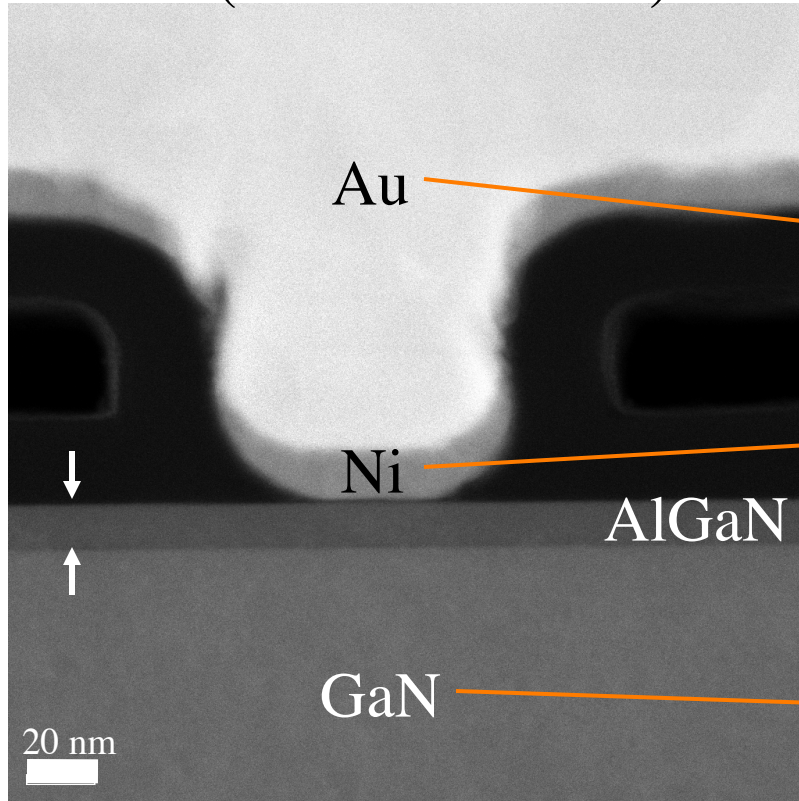
$V_{DS} = 10V$
 $V_G = -10V$ to $-42V$
• 1 min steps

- 1813

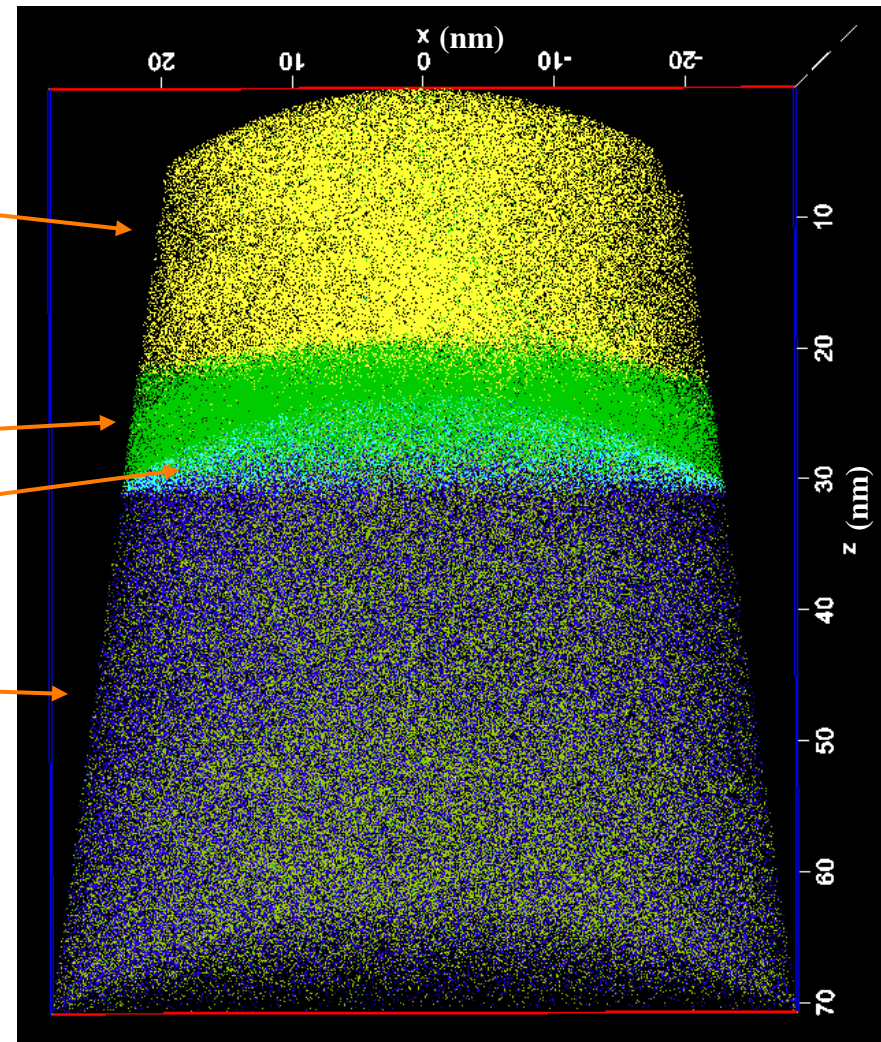


LEAP of AFRL Devices

• TEM (STEM-HAADF)



• LEAP



- Reconstruction flawed due to tip fracture/delamination
- Ni and AlGaIn layers are thin and interfaces have poor shape

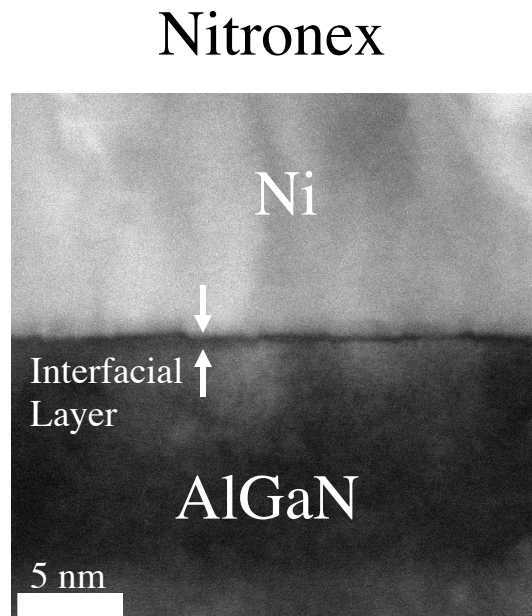
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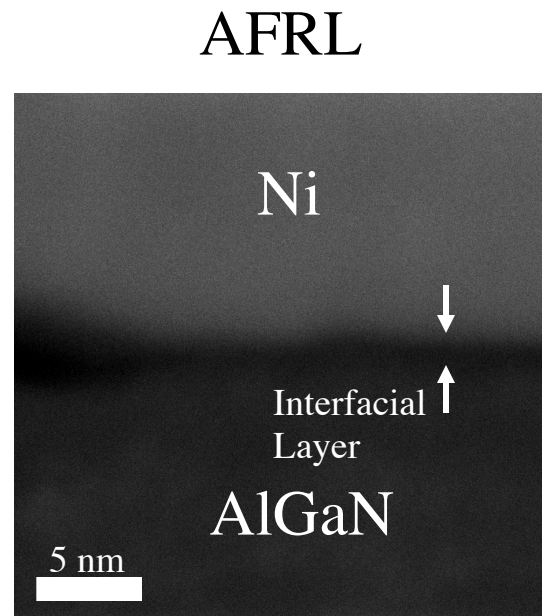
Limitation of LEAP

- Fracturing during LEAP of TriQuint and AFRL HEMTs occurs near interfaces
- Why?
 - Weak interfaces
 - Interfacial layer thickness
 - Pulsing causes stress
 - Delamination
 - Fracture
- But LEAP was successful for Nitronex devices but neither AFRL nor TriQuint?

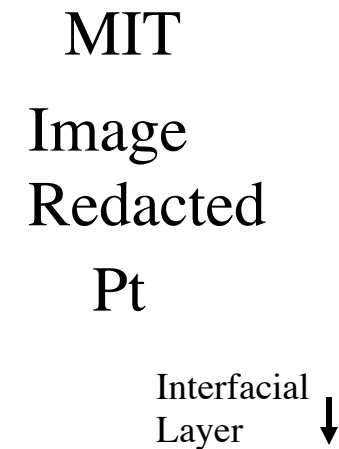
Structural difference between Nitronex, AFRL, and MIT?



$\sim 5 \text{ \AA}$



$\sim 15 \text{ \AA}$



$\sim 18 \text{ \AA}$

- Nitronex HEMTs have a smaller interfacial layer
 - Only samples that did not fracture or delaminate during LEAP analysis

How to Resolve this Issue?

- Change atom probe systems
 - University of Alabama LEAP limited to laser wavelength of 532 nm
 - Newer systems have wavelengths < 360 nm
- Why is the smaller wavelength important?
 - Larger energy
- Mechanisms for improved evaporation
 - Material with band gaps below laser photon energy
 - Direct excitation
 - Material with band gaps above laser photon energy
 - Creation of holes at tip apex from defects/surfaces/edges
 - Improves tip conductivity, enhances evaporation
 - Thermal excitation
- Who do we plan on collaborating with?
 - University of Tsukuba
 - PNNL

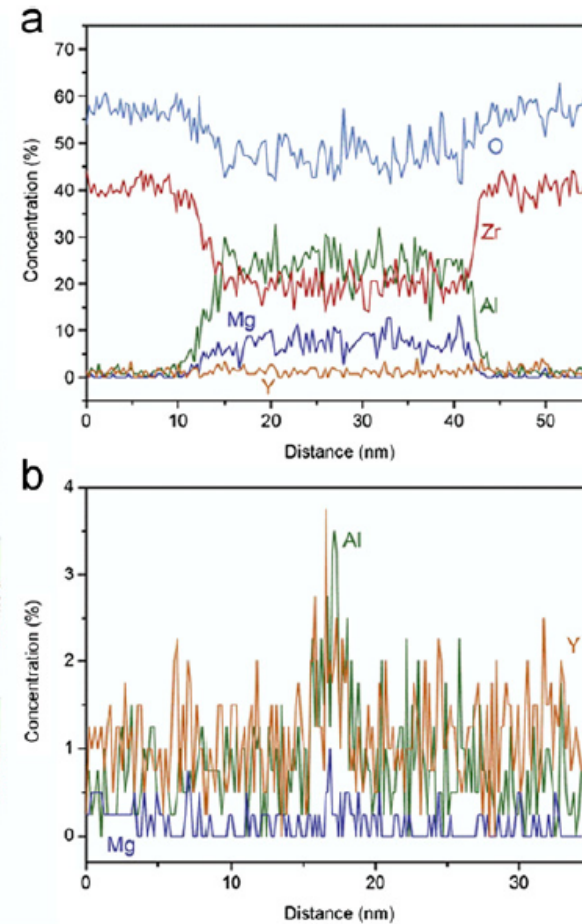
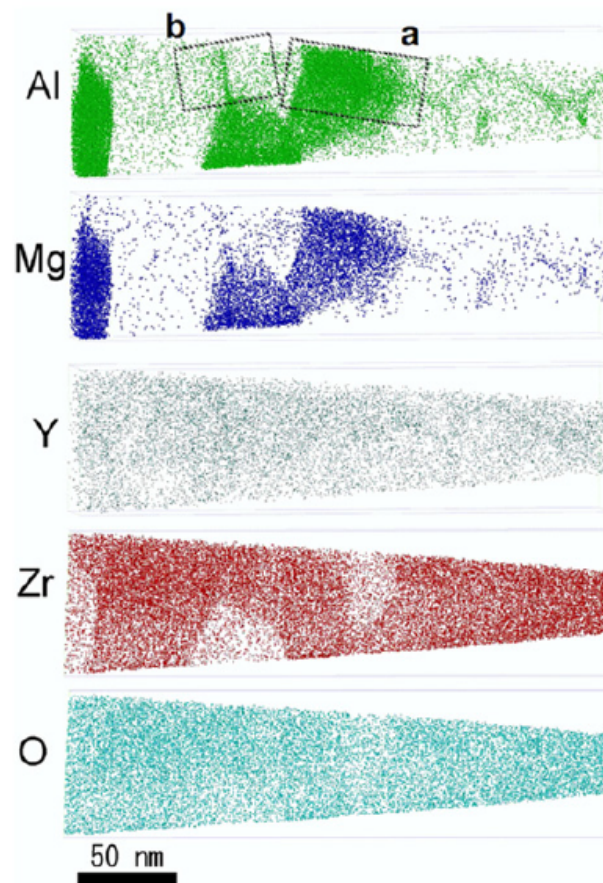
New Atom Probe Collaboration

- Dr. Kazuhiro Hono
 - MMU (Magnetic Materials Unit) formerly NIMS
 - University of Tsukuba (Tsukuba, Japan)
- Custom built atom probe
 - Four available laser wavelengths
 - 1030 nm, 515 nm, 343 nm, 258 nm
 - LEAP only has one wavelength = 532 nm
 - Shown great results working with insulating and wide band gap materials
 - ZnO, MgO, Li(Co, Ni, Mg, Al)O₂ (Li-ion battery)
- Received internship to travel there this summer to complete work
- Started this collaboration in February and were preparing first samples in March but delays occurred (Earthquake/Tsunami)

New Atom Probe Collaboration

- Some of their results on YSZ

K. Hono, *et al.*, Ultramicroscopy (2010),
doi:10.1016/j.ultramic.2010.11.020



Atom probe tomography of Al, Mg, Y, Zr and O and concentration profiles calculated from inset boxes (a) and (b)

Another Possible Atom Probe Collaboration

- PNNL (Pacific Northwest National Laboratory)
 - Dr. Theva Thevuthasan
 - Environmental Molecular Sciences Laboratory
 - Shown interest in collaborating
 - Submitting proposal to use facility
- LEAP 4000 XHR
 - Laser wavelength of 355 nm
 - Can use same sample preparation techniques we've been using

Summary

- Studied three different HEMT structures

	<u>Nitronex</u>	<u>MIT</u>	<u>AFRL</u>
Condition:	$t = 0$	$t > 0$	$t = 0$ and $t > 0$
Analysis:	TEM LEAP -Identified interfacial layer	TEM -pits LEAP -Unsuccessful	TEM -interfacial defects LEAP -Unsuccessful

- Identified three defects in AFRL devices

<u>Not Visible/Found</u>	<u>1514A</u>	<u>1813A</u>
2016A 2112A 0827C/D 1513A	<u>Stress Conditions</u> $V_{DS} = 0, 0, 5, 15V$ $V_G = -10V$ to $-42V$ Except 0827 to $-50V$ •1 min steps	<u>Stress Conditions</u> $V_{DS} = 10V$ $V_G = -10V$ to $-42V$ •1 min steps
	•Defect along entire device	•Defect along 20% device

Conclusions

- Improved LEAP analysis by incorporating orthogonal data pipes using iso-surfaces to increase interface resolution
- Begun to chemically identify interfacial defects in AFRL devices
 - AlGaIn decreases in Al and Ga
increases in In and sometimes O
 - Al and Ga appear in the defect where In part of the gate was located originally
 - Modification of the In
- Identified limitations of LEAP for HEMT devices
 - Current laser wavelength is a limitation
 - Establishing collaborations to use systems with smaller λ 's

Future Work

- EDS of AFRL interfacial defects
 - New analytical pole piece should improve detection
- EELS of AFRL interfacial defects
 - Determine N composition
 - Help determine O composition
 - In discussion with FEI on collaboration with newest TEM
- Atom Probe of AFRL devices
 - Structure and composition of defects
- Correlate chemical structure with physical defects
 - Understand formation mechanisms
- Correlate electrical signals for each defect